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*Published in:*  
Geophysical Journal International

*Link to article, DOI:*  
[10.1093/gji/ggx285](https://doi.org/10.1093/gji/ggx285)

*Publication date:*  
2017

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Herceg, M., Jørgensen, P. S., & Jørgensen, J. L. (2017). Stellar aberration correction and thermoelastic compensation of Swarm ASC attitude observations: A comment to the Express Letter “Mysterious misalignments between geomagnetic and stellar reference frames seen in CHAMP and Swarm satellite measurements”, by Stefan Maus. *Geophysical Journal International*, 211(2), 1104–1107. <https://doi.org/10.1093/gji/ggx285>

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# Stellar aberration correction and thermoelastic compensation of Swarm $\mu$ ASC attitude observations

## A comment to the Express Letter “Mysterious misalignments between geomagnetic and stellar reference frames seen in CHAMP and Swarm satellite measurements”, by Stefan Maus

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Accepted 2017 July 4. Received 2017 June 30; in original form 2017 May 9

### SUMMARY

The Swarm constellation of three satellites measures the magnetic signal of the Earth using both a Vector Field Magnetometer and an Absolute Scalar Magnetometer. A Micro Advanced Stellar Compass ( $\mu$ ASC) mounted on a common, supposedly stable, optical bench precisely determines its inertial attitude. However, comparison of the Inter Boresight Angle shows a relative attitude variation between the  $\mu$ ASC Camera Head Units. These misalignments between Camera Head Units and a geomagnetic reference frame cannot be explained by incorrect aberration correction (as theorized by Maus). Herceg *et al.* found them to be caused by thermal gradient sensitivity of the optical bench system, opposing the underlying assumption of perfect platform stability. The results after applying thermal corrections show significant decrease in root mean square, with Inter Boresight Angle of thermally corrected data being nearly flat and clean from any variation caused by thermoelastic effects.

**Key words:** Magnetic field; Satellite magnetics.

### 1 INTRODUCTION

The Swarm mission satellites measure the magnetic signal of the Earth using an Absolute Scalar Magnetometer (ASM) and a Vector Field Magnetometer (VFM). While the ASM measures magnetic field strength (and serves to calibrate the VFM instrument), the VFM measures the magnetic field vector. To precisely orient measured magnetic field vector, the three optical heads of the Micro Advanced Stellar Compass ( $\mu$ ASC) are mounted on the Swarm optical bench (OB) together with the VFM sensor. The  $\mu$ ASC is an entirely autonomous, internally redundant star tracker, designed and produced by the Measurement and Instrumentation Section at DTU Space Department, Denmark Technical University (Jørgensen *et al.* 2004). Being one of the most successful star trackers worldwide, the  $\mu$ ASC has been operating on many satellite missions, and even though subjected to very different orbital and thermal environments, not a single hardware or functional failure has ever occurred.

Swarm satellite orientation can, therefore, be determined from both magnetic field measurements and  $\mu$ ASC images. These independent measurements can be compared, and ideally, should agree. Maus (2015) presented consistent misalignments between the stellar and geomagnetic reference frames observed by Swarm satellites. In

Maus (2015), these misalignments are associated with deficiencies in the software carrying out the star camera aberration correction, as one of the possible causes, while disregarding any potential thermally induced mechanical instability. To investigate the causes of these misalignments, a study was performed (Herceg *et al.* 2017) on Swarm relative Camera Head Units (CHU) orientation and its correlation with stellar aberration and thermal variation of the OB system.

The purpose of this comment paper is to summarize the findings given in Herceg *et al.* (2017) and to explain the misalignments between CHU and a geomagnetic reference frame presented in Maus (2015).

### 2 SWARM $\mu$ ASC OBSERVATIONS

Each Swarm satellite is equipped with three CHU's, placed on the OB such that the angles between the boresights, referred to as Inter Boresight Angle (IBA), are approximately  $90^\circ$  (Fig. 1). The IBA of each CHU pair is defined as the angle between the Z-axes of the two CHU's.

The OB is an ultrastable silicon carbide–carbon fiber compound structure (Pereira & Rathband 2012) with the main purpose of

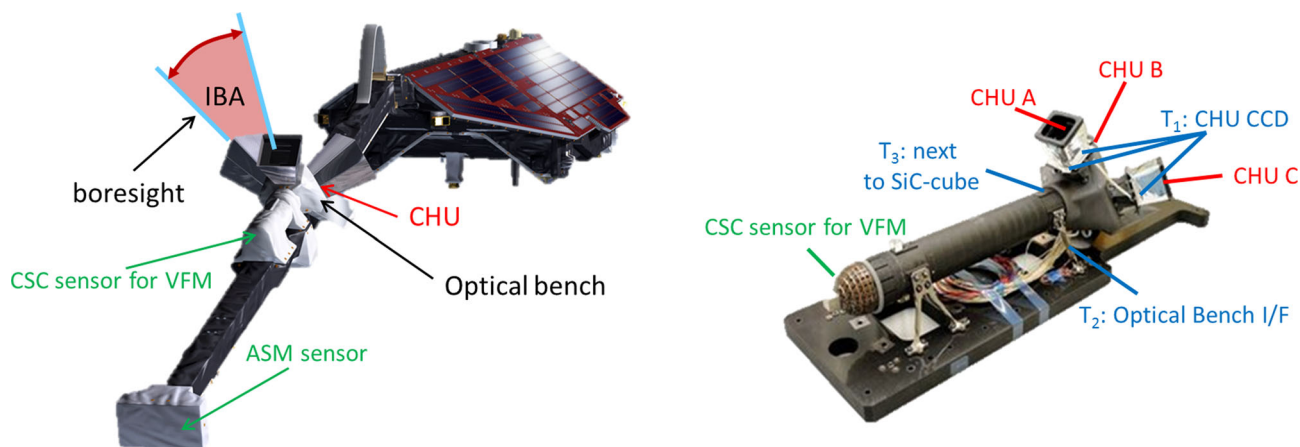


Figure 1.  $\mu$ ASC mounted on Swarm satellite (left) and optical bench thermistors (right).

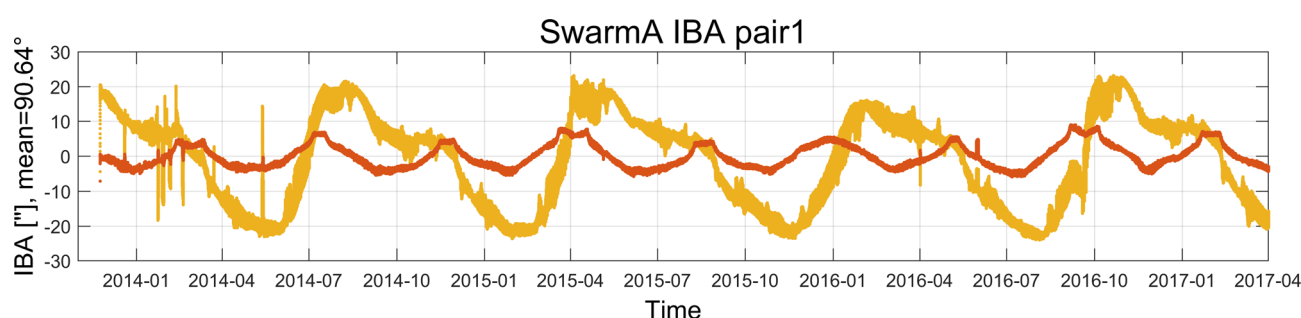


Figure 2. Swarm Alpha, CHU pair 1, original (yellow) and aberration corrected (red) IBA (the mean value of  $90.64^\circ$  is subtracted).

transference of the precisely determined  $\mu$ ASC attitude to the VFM. Prior to the Swarm launch, exhaustive thermomechanical analyses were carried out to ensure thermal and mechanical stability; however, this stability cannot be monitored directly in flight. Instead, an indirect approach for testing OB stability is used in which the thermal state of the OB is monitored and compared to the IBA variation. The thermal state is observed using the thermistors mounted on different parts of the OB, as shown in Fig. 1.

Before calculating IBA and comparison with thermal variation, attitudes obtained by the Swarm CHU's have to be corrected for stellar aberration. Generally, the aberration correction is carried out automatically on-board. However, as the Swarm velocity information is not available immediately to the  $\mu$ ASC instrument, stellar aberration correction is applied on the ground during post-processing (contrary to the claim of Maus 2015). The details describing the algorithms for the Swarm data processing can be found in Tøffner-Clausen & Holmdahl Olsen (2015).

### 3 MODELLING OF THE THERMOELASTIC EFFECTS OF OPTICAL BENCH

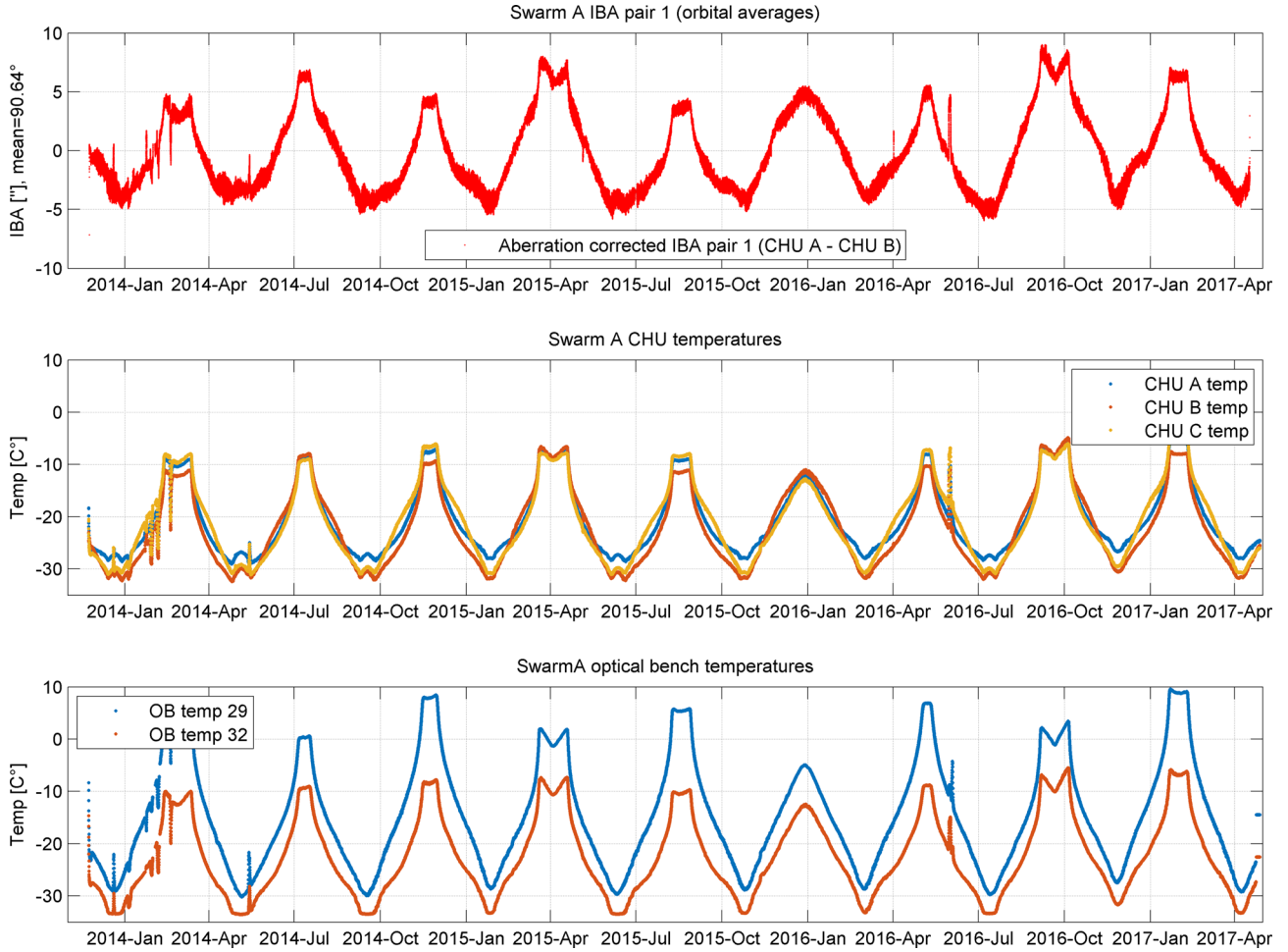
The IBA is the most accurate relative comparison of the CHU stability. Therefore, it is used as a primary means of comparison in the further analysis. This choice is guided by the accuracy of measured orientation, which is highest in CHU pointing direction (along the camera boresight). In the analysis of the IBA stability,

the root mean square (RMS) value of the data is used to assess the IBA stability. When comparing the IBA of aberration corrected with uncorrected attitude data, results show significant improvement in stability of the CHU's (see Fig. 2 for Swarm Alpha results), where RMS of the IBAs is reduced by  $\sim 13$  arc-seconds.

Ideally, the IBA of aberration corrected attitudes is expected to be constant. However, the IBA on Fig. 2 (red curve) shows a variation which is correlated with a periodicity of temperature observations (Fig. 3).

The comparison shows that IBA variation of aberration corrected data has a thermal signature, which has maximum effect when the satellite orbit plane is dawn–dusk oriented (hottest configuration) and minimal in the noon–midnight orbit. The observed thermal variation is causing OB instability, and needs to be modelled using the OB thermistor data (Fig. 3). For that purpose, a thermal compensation model was derived as explained in Herceg *et al.* (2017). The temperatures selected for thermal modelling are those observed by the CHU and OB thermistors (THT00029—next to the optical cube, and THT00032—Optical Bench I/F, see Fig. 1), to ensure the correct profile of the thermal gradient.

After applying the thermal correction, the comparison of aberration corrected and thermal corrected data is made (see Fig. 4 for Swarm Alpha, where green dashed line represents the period from 2014 June 16 to 2015 December 3 for which model was determined). Results for Swarm Alpha show the largest correction (Fig. 4) for the first (CHU A—CHU B) and the third (CHU B—CHU C) IBA pair. Both of these IBA pairs have CHU B in common, which indicates that the main correction is applied when CHU B is involved. The



**Figure 3.** Swarm Alpha IBA (top, the mean value of  $90.64^\circ$  is subtracted), CHU temperature (middle) and optical bench (OB) temperature (bottom). OB temperatures are measured in two locations as seen in Fig. 1.

reason for this might be CHU B placement on the OB, where the CHU mounted on a very edge of the OB may cause such thermal gradient signatures.

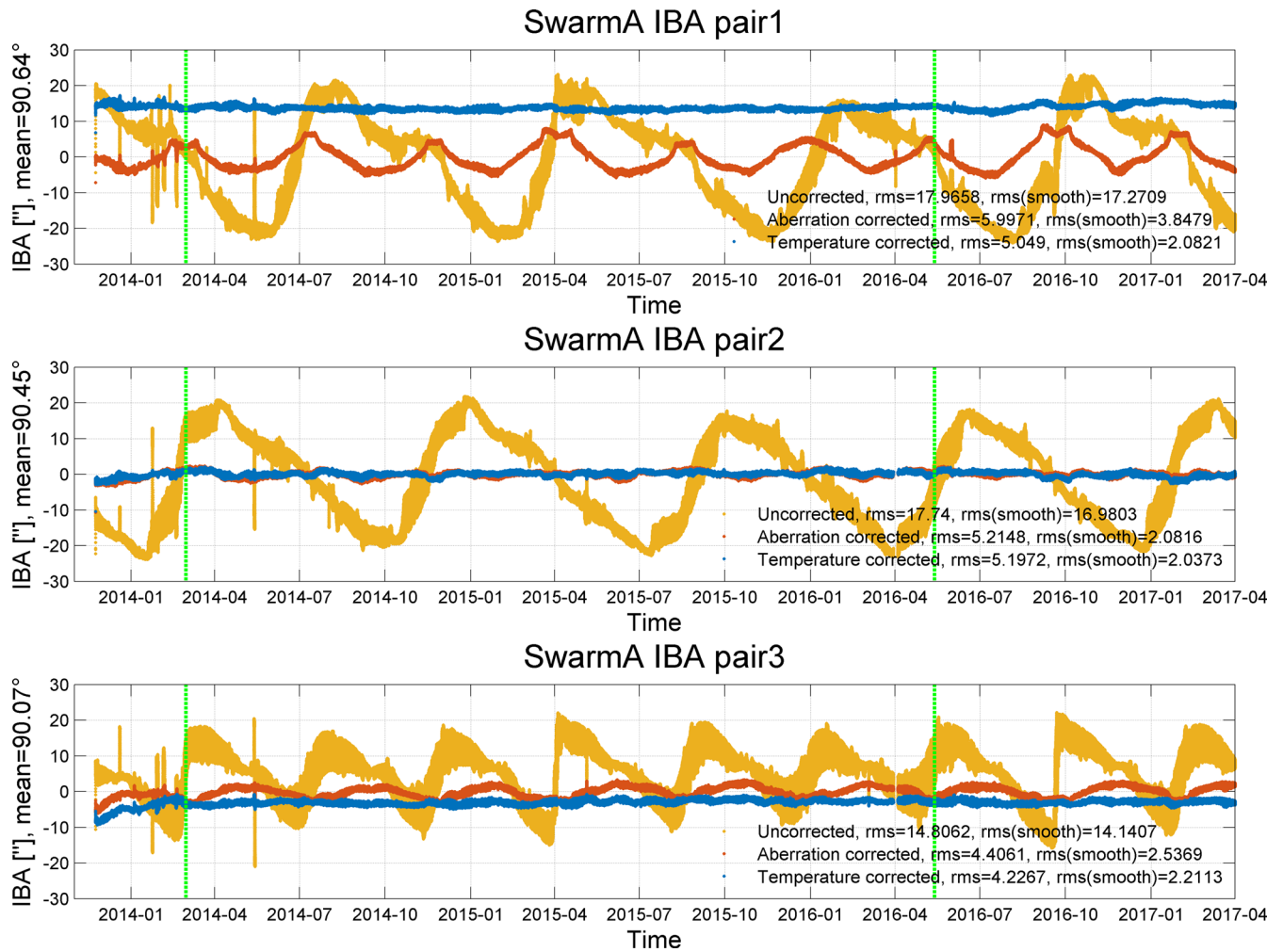
The RMS values given for each panel in Fig. 4 show results of the complete data set and a version smoothed over 200 s windows (to suppress short-term noise sources). The RMS of the IBA pairs for Swarm Alpha is reduced down to 2.2 arc-seconds, with IBA of thermally corrected data being virtually constant. The same improvement is also notable for the corrected data outside of the modelling period (green dashed lines on Fig. 4), where stability of the IBA shows excellent results in thermal effects prediction. Furthermore, the bias per CHU is assumed to be smaller than  $1/\sqrt{2}$  times value presented in Fig. 4, considering the IBAs RMS contains measurements of two cameras.

As presented here, the aberration correction is performed correctly and residual IBA variation, which is apparently driven by thermal gradients, can be adequately compensated by a thermal model described in Herceg *et al.* (2017). These results are contrary to the fundamental assumption in Maus (2015), where a perfect OB system and a flawed aberration correction are used to explain the observed IBA variations.

## 4 CONCLUSIONS

Periodical variations in relative CHU orientation on the Swarm satellites are found to be caused by two phenomena: stellar aberration and thermoelastic effects of the OB. The  $\mu$ ASC attitude data are not corrected for aberration on-board (although feasible), since the spacecraft velocity information is not immediately available to the instrument, and is, therefore, performed during ground data processing. After aberration correction, the angle between the CHU boresights (IBA) is expected to be in the one arc-second range. However, a small, but significant signal remains in the IBA data, which is found to be correlated with temperature variations (Herceg *et al.* 2017). Therefore, an additional correction is applied on Swarm  $\mu$ ASC attitude data for compensation of thermoelastic effects. The results after thermal correction show a decrease in RMS for Swarm Alpha down to 2.2 arc-seconds, with IBA of thermally corrected data being virtually constant and clean from any thermally induced phenomenon.

Contrary to the basic assumption in Maus (2015), where a perfect OB system and a flawed aberration correction are used to explain the observed IBA variations, this study proves that aberration correction is performed correctly and residual IBA variation can be



**Figure 4.** IBA angle for Swarm Alpha: original (yellow), aberration corrected (red) and temperature corrected including pre-flight calibration offset (blue). The mean IBA value is subtracted from each IBA pair and equals to 90.64° for pair 1, 90.45° for pair 2 and 90.07° for pair 3. Green dashed lines limit the period for which model is estimated.

fully compensated by a simple thermoelastic model using on-board measured temperatures.

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